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EXPERIMENTAL VALIDATION OF THE INTERACTION BETWEEN COMBUSTION AND STRUCTURAL VIBRATION

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Abstract

To decrease NOx emissions from combustion systems, lean premixed combustion is used. A disadvantage is the increase in sound pressure levels in the combustor, resulting in an increased excitation of the surrounding structure: the liner. This causes fatigue, which limits the life time of the combustor.

To study this problem experimentally, a test setup has been built consisting of a single burner, 500kW, 5 bar combustion system. The thin structure (liner) is contained in a thick pressure vessel with optical access for a traversing laser vibrometer system to measure the vibration levels and mode shapes of the liner. The acoustic excitation of the liner is measured using pressure sensors measuring the acoustic pressures inside the combustion chamber and in the cooling passage between the liner and the pressure vessel.

To validate models, measurements were performed in steps of increasing complexity. Firstly, the structural properties, obtained by modal analysis of the liner outside the pressure vessel, have been compared with a finite element model. Subsequently, results of an acoustic finite element model of the setup have been compared to acoustic measurements on the test rig to validate the acoustic properties of the model, which are made by mounting a well defined acoustic source to the rig. Finally, measured pressures and vibration levels in the presence of combustion are shown.

The results show that numerical and experimental mode shapes of the liner outside the pressure vessel agree well and even for the fired setup, the mode shapes can be matched. The structural eigenfrequencies can also be predicted well. The acoustic response of the setup agrees well with simulations and is also found in the combusting setup.

INTRODUCTION

To decrease NOx emissions from industrial gas turbines, lean premixed combustion (using a surplus of air to burn the fuel) is used.[5] A consequence of the lean combustion is higher sound pressure levels in the combustion system. The annular liner (the surrounding plate-like structure of the combustion chamber), which is often used, has a relatively low stiffness and will therefore vibrate excessively due to these sound pressures. This limits the life time of the combustor and the range of operability, because of failure due to fatigue.

There are two approaches to overcome this problem. The most common approach is to decrease the acoustic pressure levels in the combustor.[4] The other approach is to decrease the vibration level of the liner by, for instance, increasing its damping. This requires investigation of the fluid structure interaction between the liner, the combustion chamber and the cooling passage surrounding the liner. The European project DESIRE (DESIgn and demonstration of highly REliable low NOx combustion systems for gas turbines) is concerned with this interaction. In this project the structural response of the liner in a 500 kW test-rig is measured. Previous papers showed the experimental validation of a simplified fluid structure model,[3] a fluid structure model that is closer to the experimental setup[2] and a model that includes the effects of combustion.[1] In this paper experimental results are described and compared with numerical predictions.

EXPERIMENTAL SETUP

A cross section of the experimental setup is depicted in figure 1. It consists of three separate, square sections. Air enters the setup in the burner section, which contains the

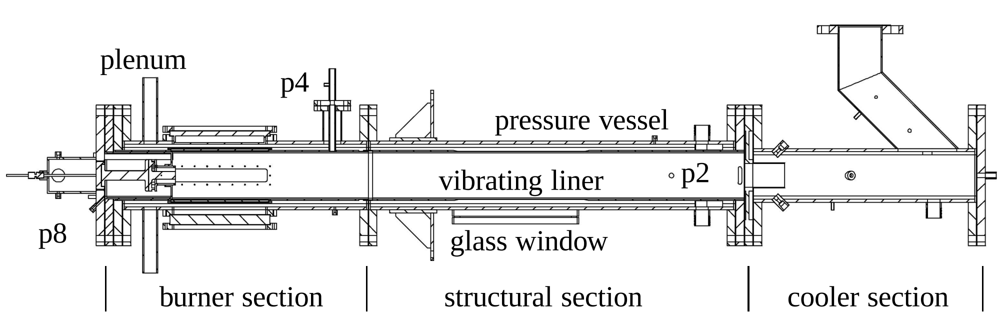

Figure 1: Cross section of the test rig with the locations of the pressure transducers

plenum, burner and the first part of the combustion chamber. The hot flue gasses move on to the structural section containing the liner part with reduced thickness on which the vibrations are measured. Finally, in the cooler section the flue gasses are cooled down by waterinjection. The liner is contained in a pressure vessel to allow measurements at elevated pressure, with cooling air flowing between liner and pressure vessel. Glass windows are mounted in this pressure vessel at the structural section through which a Polytec laser vibrometer can measure the vibration level. Pressure sensors are mounted at several locations to measure the acoustic pressure perturbations in the combustion chamber, plenum and cooling passage (several of these sensors and their numbers are also depicted in figure 1).

The experiments were done in several stages with increasing complexity. Modal analysis was first performed on the liner part with the thin section outside the setup. After this the liner was mounted in the setup. The structural as well as the acoustic properties of the setup without combustion were measured. Finally, the vibration response during combustion was measured.

STRUCTURAL EXPERIMENTS

To analyze the properties of the structural liner (which is inside the structural section, figure 1), modal analysis was performed on this part. The liner consist of thick end parts (4 mm) with a thin part (1.5 mm) welded in between. The thin part also consists of U-shaped plates that are welded together. These welds introduce a priori unknown structural behavior to the liner, and therefore the eigenfrequencies and mode shapes were measured before it was mounted inside the test rig. The measurements were made by traversing a laser vibrometer over one side of the square liner, sequentially making measurements on different points (figure 2). The resulting eigenfrequencies are shown in table 1, in which the same mode designation is used as in a previous paper.[2] Numerical results are also included, which have been calculated using a structural finite element model of the full liner including end flange. The welds have been approximated. The agreement is good, considering the welds in the construction.

ACOUSTIC EXPERIMENTS

The acoustic measurements were carried out for two main reasons. Firstly, they provide insight in the real acoustic behavior of the test rig (such as acoustic eigenfrequencies and influences of unmodelled components), which facilitates interpretation of data obtained while there is a flame in the test rig. Secondly, the data can be used to validate the acoustic part of models that are made of the setup.

To do acoustic experiments, a box with a speaker inside is connected to a plug in the cooler section via an aluminum tube (figure 3). The source is driven by a chirp signal, generated by a SigLab dynamic signal analyzer and amplified by a Brüel and Kjær 2706 amplifier. Kulite pressure transducers are used, of which the locations are

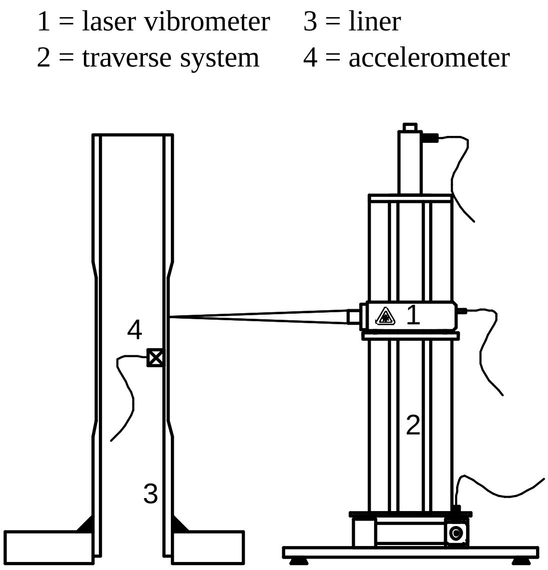

Figure 2: Structural measurements

mode	meas. [Hz]	calc. [Hz]
beam bending	-	115.2
(1,1)	181.5	188.9
squeeze 1	224.0	243.2
(2,1)	239.0	263.9
(1,1) half	269.5	273.1
(2,1) half	285.0	337.9
(3,1)	316.5	361.3
squeeze 2	327.5	439.2
(1,1) volumetric	392.0	380.9
(4,1) strong upper	370.5	418.5
(2,1) volumetric	443.0	433.6
(3,1) half	446.0	438.3

Table 1: Structural eigenfrequencies

shown in figure 1 (p2, p4 and p8). The sound pressure generated by the speaker as measured by the pressure pickups is around 100 dB for all sensors. The measured autospectra for two sensors are depicted in figure 4.

Table 2 shows the acoustic eigenfrequencies that were calculated using an acoustic finite element model of the geometry including plenum, combustion chamber and water cooler, but without the influence of the flexible liner and cooling passage. The measured acoustic eigenfrequencies have been determined by searching for peaks in the autospectra as shown in figure 4. It can be seen that there is a fair agreement between the measured and calculated eigenfrequencies. There are more peaks in the spectrum though, some of which are probably caused by resonances of the flexible structure and

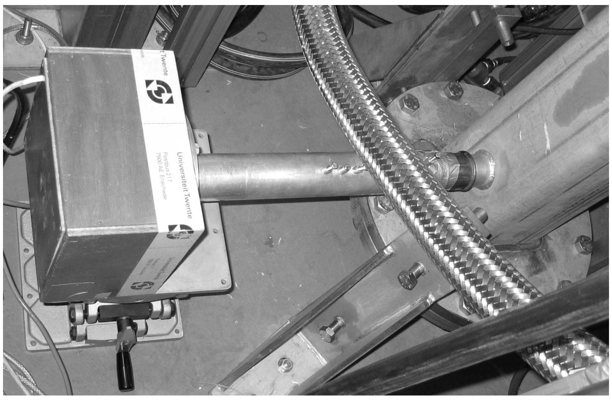
Figure 3: Acoustic source for acoustic experiments on the test rig

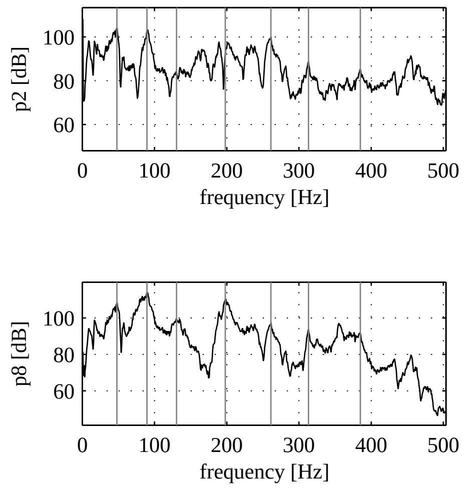

Figure 4: Measured autospectra, gray lines are eigenfrequencies

mode	meas. [Hz]	calc. [Hz]
cooler (0,0,0)	48.0	54.4
plenum	89.5	94.2
(1,0,0)	130.5	133.9
(2,0,0)	198.0	206.0
cooler (1,0,0)	261.2	260.6
(3,0,0)	313.2	301.6
(4,0,0)	385.0	391.6

Table 2: Measured and calculated eigenfrequencies

others by the unmodelled acoustics of the cooling passage. Due to the limited amount of pressure sensors, little spatial detail can be obtained in the pressure measurements, but because the eigenfrequencies match well, the acoustic mode shapes are assumed to be the same as the calculated ones.

Besides the eigenfrequencies, the transfer functions between two pressure sensors are also compared to gain more insight in the accuracy of the model. Two transfers are used for this, between sensors p2 and p4 (both in the combustion chamber) and p2 and p8 (combustion chamber and plenum). These transfer functions are depicted in figure 5. It can be seen that the match is far from perfect. This is not really surprising, because an exact transfer function match is hard to achieve in a complex setup, because not the resonances but the zero pressure points are very important for the shape of the transfer function. It should also be noted that the model only contains the acoustics of the combustion chamber. Both cooling passage and flexible liner are not taken into account, but still some agreement can be observed. In the low frequency region, the transfer from sensor p2 (combustion chamber) to p8 (plenum) is predicted well. This is probably because this transfer is dominated by the resonance of the plenum on the combustion chamber. Furthermore, the transfers for higher frequencies (above 400 Hz) also match well. In the region in between the correspondence is not very well.

COMBUSTION EXPERIMENTS

Structural and acoustic measurements have also been performed during combustion. The results shown in this paper were obtained at a pressure of 1 bar and a thermal power of 100 kW. Vibration measurements were performed, on an equidistant grid of

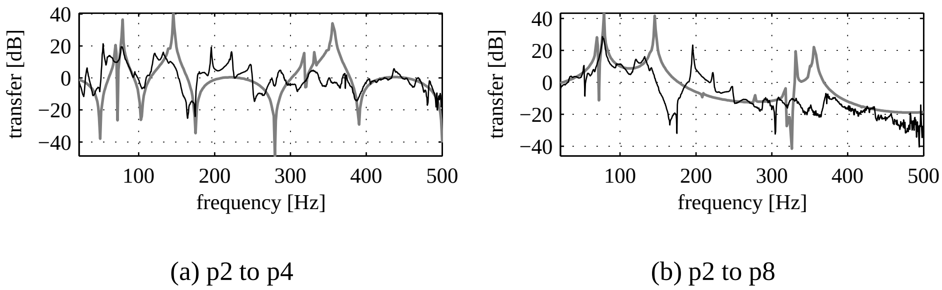

Figure 5: Experimentally (black) and numerically (gray) determined acoustic transfer functions

15 points, through a slit window in the pressure vessel, covering 340 mm of the 400 mm long flexible liner part (figure 6). The first measurement point was approximately 10 mm above the lower weld between the stiff and the flexible part of the liner and the last point was 50 mm below the upper weld (see also figure 2). The eigenfrequencies that were found are listed in table 3. The corresponding mode shapes as measured through the slit window are depicted in figure 6.

There was no accurate reference that could be used, which means that no phase information is available and therefore parts of the structure moving inwards or outwards cannot be distinguished. Nevertheless, mode shapes can be recognized using the previously made calculations. Modes 2, 4, 5 and 6 are the first local modes of the flexible section, which were measured in the cold setup in this sequence. The first mode at a rather low frequency of 124 Hz has a low contribution to the vibration. In previous measurements this was often related to global modes, which can be substantially damped by friction effects at the ends of the thick parts. This is therefore probably the first bending mode of the entire liner. The mode at 220 Hz, with quite a strange shape, is probably a squeeze mode, though it has a large participation, where in cold measurements it was hardly distinguishable. This might be due to the excitation, which in cold measurements was a shaker on the flexible part, while now the entire structure is acoustically excited. The acoustic pressures also increase around this frequency, which

number	frequency [Hz]	possible shape	cold frequency [Hz]
1	124.0	first bending	
2	195.5	(1,1)	181.5
3	220.0	1st squeeze	224.0
4	262.5	(2,1)	239.0
5	287.0	(1,1)	245
6	324.5	(2,1)	285

Table 3: Resonance frequencies of the structure during combustion

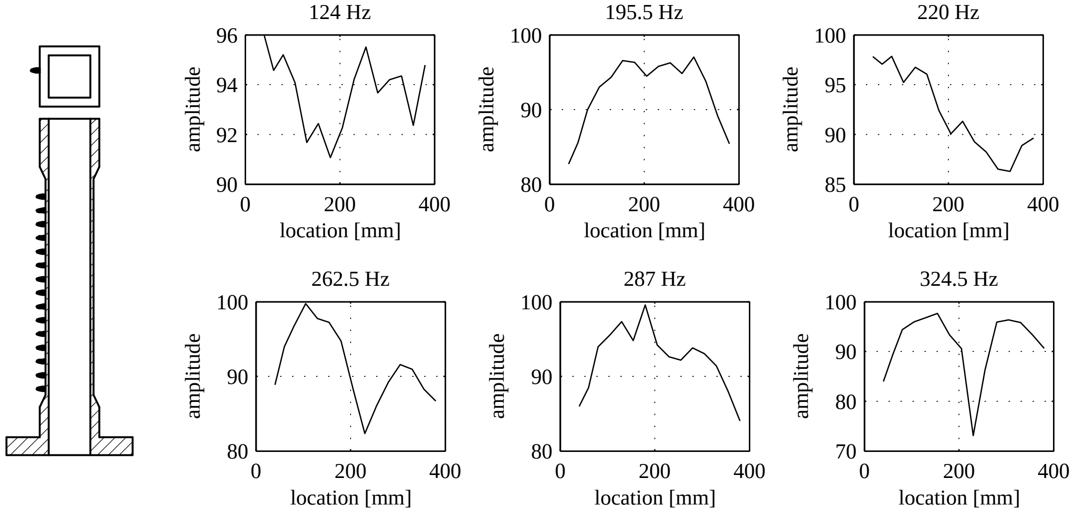

Figure 6: Measurement grid (left) and mode shapes resulting from the vibration levels measured through the slit window

may add to the stronger presence of this mode.

Figure 7 shows the autospectrum of the signal measured by pressure sensor p2. It can be seen that it is fairly constant at levels around 110 dB between 50 and 400 Hz, but strongly increasing in the region above 400 Hz. This may be related to the second acoustic mode, which has a frequency of approximately 463 Hz at a combustor temperature of 1600K.

The autospectrum of the vibration measured with the laser vibrometer is depicted in figure 7 (right). It can be seen that significant vibration starts just below 200 Hz, which coincides with the first structural eigenfrequency of the liner. Before this frequency there is only one sharp peak of a global mode at a lower frequency. After this first mode of the flexible section, several more modes are clearly distinguishable. Above 300 Hz, modal density increases and therefore the average vibration level also increases, which is also partially caused by increasing acoustic pressure levels.

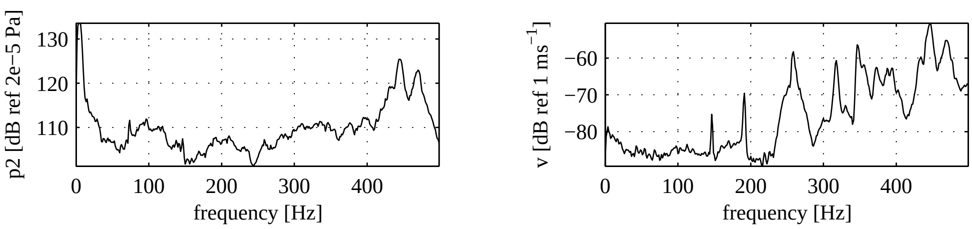

Figure 7: Autospectrum of pressure sensor p2 (left) and laser vibrometer (right)

CONCLUSION

Results were shown of three different measurements to determine the structural and acoustic behavior of a combustion setup: modal analysis on the structure, acoustic measurements on the setup without combustion and measurements during combustion. The structural model gives a fairly good prediction of the liner behavior, with the presence of welds being the most likely explanation for the differences. The same structural modes are observed during combustion, with somewhat different frequencies due to temperature influences. The acoustic modes of the cold system are also predicted fairly well, although the model does not yet include the coupling to the structure.

Future work will include comparing previously developed models with fluid structure interaction for the combusting setup with the measured results. When numerical models and experimental results agree fairly well, the numerical model can be used to predict liner vibration and lifetime for different configurations finding the most robust one.

ACKNOWLEDGEMENTS

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